11

Radar Systems

Radar is a short form of *Radio Detection and Ranging.* It is being used extensively these days for gathering information about distant objects, or targets, by sending electromagnetic waves at them and analysing the received echoes. Radar was developed more or less simultaneously in United States, Germany, Great Britain and France a few years before World War II.

Radar has been in use in war and peace for a variety of applications ranging from an instrument for giving warning about enemy planes to weather mapping applications. Early warning Radars, such as used in the *Distant Early Warning* (DEW) line, are large ground based installations employing huge parabolic reflectors or arrays or stationary dipole antennas.

The war-time applications of Radar were soon expanded to include Ground control of interceptor aircraft (GCI) and the direction of Antiaircraft Gun and searchlights by means of Radar. These so called, Fire Control Radars, not only detect the enemy planes, but also automatically direct the Antiaircraft Guns that fire upon them. Warning and fire control Radar eventually become airborne and are now included in most military aeroplanes. Radar find use as Altimeters to measure the distance of a plane from the ground directly beneath it. Conventional pulse type Radars can be used to measure the absolute altitude of an airplane above the surrounding terrain, provided the plane flies at a considerable height. At very low altitudes (*i.e.* below about 1000 feet) however, the pulse type Radar becomes unsatisfactory, since for short distances involved, the echo pulse tends to merge with the transmitted main pulse.

Therefore, most Radar Altimeters use continuous frequency modulated waves. In addition, Radar finds important uses such as to find the locations of land masses, ships, marker buoys, directing guided missiles, searching for submarines, aiding night fighter aircraft in locating and attacking enemy aircraft, aiding the landing of aircraft under adverse weather conditions (*i.e.* poor visibility), in monitoring air traffic in the vicinity of airports, as a speed detector used by police etc.

11.1. Basic Principles

Basically, a Radar System block diagram has four blocks namely Transmitter, Receiver, Duplexer and Antenna as shown in Fig. 11.1. The transmitter is capable of sending out large U.H.F. or Microwave Power through a directional antenna. The associated receiver collects as much energy as possible from the received echoes reflected in its direction by the target, analyses it and displays this information in a suitable way; often the same antenna is used for transmitting as well as receiving ; this being achieved by a Time Division Multiplexing System arrangement called duplexer (details to follow). Referring to Fig. 11.1, the transmitter generates rectangular pulses which are transmitted by the antenna towards the target, a small fraction of the transmitted power reflects back toward the antenna, which is directed by the duplexer to the receiver which subsequently analyses and displays it on an indicator in perfect synchronism with the sequence of events which are as follows.

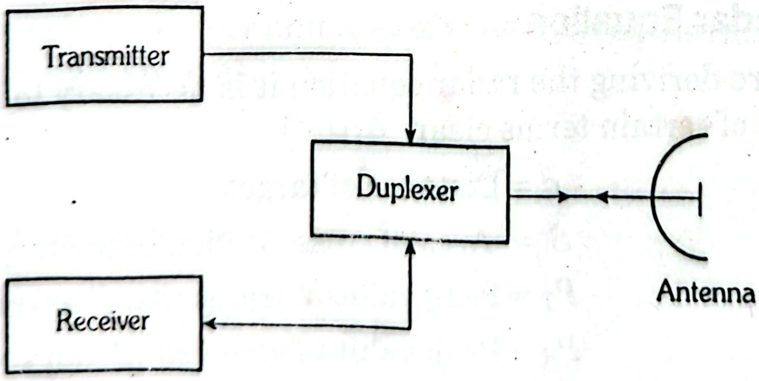


Fig. 11.1. Block diagram of an elementary pulsed radar.

The transmitter generates a pulse in response to an internally generated trigger signal. As soon as a fraction of power to be transmitted reaches the duplexer it disconnects the receiver from the antenna and connects the transmitter to it. The highly directional pulse is then transmitted and directed at the target. As soon as the transmitted pulse ends, the duplexer disconnects the transmitter from the antenna and connects the receiver to it, so that the receiver can accept the echo pulse when it arrives. The received echo power is amplified and then demodulated by receiver which is then displayed. This radar is able to show the position of the target, because the information about the azimuth (horizontal direction) and the elevation (vertical direction) available is from the antenna drive motor. The distance of the target is calculated automatically from the total time taken by the pulse in the two journeys. The return distance covered in one microsecond is 984 feet which can be calculated from the velocity of electromagnetic radiations (nearly 186,000 miles per second). Thus the target must be 984/2 = 492 feet which can be approximated to 500 feet if a pulse is received 1 microsecond after transmission. Nautical mile (6080-27 feet) is the unit of distance often used in radar distance measurements and it requires 12.4 micro sec, for the electromagnetic waves to travel this distance. Thus if a range is to be 50 nautical miles, at least 620 micro sec, must elapse from a time a pulse is transmitted to the time at which the duplexer disconnects the receiver from the antenna, because the next pulse is due. Also pulse repetition frequency (P.R.F.) must be quite high compared to the scanning speed, so that a limit exists on the smallest number of pulses that can be sent per second. This results in a P.R.F. of several hundred, having a duration about of 1 micro sec.

Pulse modulated, high powered magnetrons or klystrons are mostly used as transmitter output tubes, and the first stage of the receiver is often a crystal mixer.

11.2. Radar Equation

Before deriving the radar equation it is necessary to make the meaning of certain terms clear.

Let d = Distance of target

S = Area of cross–section of the target

P_T = Peak value of transmitted power

P_R = Peak value of received (Echo) power

G_T = Power gain of transmitting antenna in relation to that of isotropic radiator

G_R = Power gain of receiver antenna in relation to that of an isotropic radiator

A = Capture area of receiver antenna

A_0 = Aperture area of receiver antenna

$k = A/A_0$ ratio of capture area and temperature area of receive antenna

0.65 for parabolic reflector

0.90 for mattress antenna.

Now power transmitted in the direction of the target = $P_T \cdot G_T$ (since G_T is the directive gain and we use highly directive antenna). Now the whole of this energy is spread around in a sphere of radius *d*, *i.e.* distance of target from the transmitter.

Area of surface of the sphere

$$= 4\pi d^2$$

Power density transmitted

$$= \frac{P_T G_T}{4\pi d^2} \qquad \text{...(11.1)}$$

Since *S* is the target area, hence power at the target

$$= \left[\frac{P_T G_T S}{4\pi d^2}\right] \qquad \text{...(11.2)}$$

After striking the target, this energy is scattered in different directions and as a result a portion of this scattered energy goes toward receiving antenna as well. Now if we suppose the total power contained in a wavefront section, having area *S* radiated by an isotropic radiator located at the target, strength of the wave thereby reaching the receiving antenna would be the same as the strength of the actual echo produced by the target.

The echo power per unit area of wavefront at the radar receiver is accordingly given as

$$= \frac{P_T G_T S}{4\pi d^2} \cdot \frac{1}{4\pi d^2} \qquad \text{...(11.3)}$$

Total received power

$$P_R = \frac{P_T G_T S}{(4\pi d^2)^2} \cdot A \qquad \text{...(11.4)}$$

Capture area, *A* is related to G_R as

$$G_R = \frac{4\pi A}{\lambda^2} = \frac{4\pi k A_0}{\lambda^2} \qquad \text{...(11.5)}$$

where λ is the wavelength. When same antenna is being used for transmission as well as reception of energy, as in present case, we have

$$G_T = G_R \qquad \text{...(11.6)}$$

$$P_R = \frac{P_T G_T S}{16\pi^2 d^4} \times \frac{\lambda^2 G_T}{4\pi} = \frac{P_T S \lambda^2 G_T^2}{64\pi^3 d^4} = \frac{P_T S \lambda^2}{64\pi^3 d^4} \times \frac{16\pi^2 k^2 A_0^2}{\lambda^4} = \frac{P_T S A_0^2 k^2}{4\pi \lambda^2 d^4}$$

From Eq. (11.5),

$$A = \lambda^2 G_R/4\pi$$

$$= \lambda^2 G_T/4\pi \qquad \text{...(11.7)}$$

We get,

$$P_R = \frac{P_T S \lambda^2 G_T^2}{64\pi^3 d^4}$$

$$= \frac{P_T S A_0^2 k^2}{4\pi d^4 \lambda^2} \qquad \text{...(11.8)}$$

If $P_{R\,min}$ is the minimum power received by the receiver antenna, then the maximum distance of the target detectable by the radar, d_{max} is given by

$$d_{max} = \left[\frac{P_T S A_0^2 k^2}{4\pi \lambda^2 P_{Rmin}}\right]^{1/4} \qquad \text{...(11.9)}$$

Eq. (11.9) is used to explain the various factors on which the Radar Range, *i.e.* d_{max} depends.

We can clearly see that

$$d_{max} \propto P_T^{1/4}, \sqrt{A_0}, S^{1/4}$$

Also $$d_{\max} \propto \frac{1}{\sqrt{\lambda}} \text{ and } \frac{1}{P_{R\,min}^{1/4}}$$

Now we will discuss in the next section as regards the choice of the factors which need be altered to increase the radar range.

11.3. Factors Influencing Maximum Range

As is clear from the radar range Eq. (11.9), the maximum range of a radar is directly proportional to the fourth root of the peak transmitted pulse power. In other words, the peak power must be increased 16 times, everything else remaining constant, if an existing maximum range of a radar is to be doubled. Obviously, such a power increase becomes uneconomical in any particular radar system.

Similarly a decrease in the minimum receivable power will have the same effect as raising the peak value of transmitting power and hence may be an equally suitable choice for increasing the radar range. But here in case of decreasing $P_{R\,min}$, a number of other factors are involved. Because of the fact that $P_{R\,min}$ is governed to a great extent by the sensitivity of the receiver, and hence, noise figure, the minimum power receivable by the receiver may be reduced by an increase in the gain of the receiver, accompanied at the same time, by a noise reduction at its input. But this may result in the receiver being more susceptible to jamming and interference because now the receiver relies more on its ability to amplify weak signals and less on the transmitted and received pulse power; hence in practice some optimum between transmitted and received power (minimum) must always be approached.

The reason as to why the radar range $d_{max} \propto P_T^{1/4}$ is that the signals are subjected twice to the operation of inverse square law—once while being transmitted and second time while being received. Same is true for any other factor which undergoes double application of the inverse square law.

Further from Eq. (11.9), we see that $d_{max} \propto \sqrt{A_0}$, where A_0 is the capture area and hence $d_{max} \propto$ diameter of the antenna provided the wavelength remains constant. This is due to the reason that the capture area, A and aperture A_0 of an antenna are related by a constant k which depends on the nature of the antenna. The aperture A for antenna is directly proportional to its (diameter)^2, hence $d_{max} \propto$ diameter of the antenna. Thus, we may say that, possibly, the best way to increase range of a radar (say double), is to double the effective diameter of the antenna, which is equivalent to doubling its actual diameter, if a parabolic reflector is being used.

As an alternative, a reduction in wavelength may be employed for the same purpose of, say, doubling the radar range, or in other words, frequency may be increased to increase the maximum radar range. But there is a limit to this increase in frequency as well. As is known from the discussion regarding beamwidth of an antenna,

$$\text{Beam width} \propto \frac{\text{Wavelength}}{\text{Diameter of antenna}}$$

So that any increase in the diameter to wavelength (D/λ) ratio will reduce the beam width. This reduction in beam width is very useful in some radar applications in which good discrimination between adjoining targets is required but it is a disadvantage in some *Search Radars*, whose function is to sweep a certain portion of the sky and which will take a longer time in case the beam width is smaller.

And finally, Eq. (11.9) shows that the maximum radar range depends on the target area, S. $d_{max} \propto S^{1/4}$. As a matter of fact, this factor is not a controllable factor.

11.4. Effects of Noise

As discussed in the previous section, the radar range can be increased by decreasing the minimum receivable power which in turn depends on the sensitivity of the receiver and hence on its noise figure.

$$\text{Noise figure, } = F = \frac{\text{Input signal to Noise Ratio}}{\text{Output signal to Noise Ratio}} \qquad \text{...(11.10)}$$

From the above definition of noise figure, in Eq. (11.10), we can calculate quantitatively, the noise power generated at the input of the receiver, P_{nri} ; this is power required at the input of an ideal receiver having the same noise figure as the practical receiver. Therefore, we have

$$F = \frac{(S/N)_{input}}{(S/N)_{output}}$$

$$= \frac{P_{si}}{P_{so}} \cdot \frac{P_{no}}{P_{ni}}$$

$$= \frac{P_{si}}{G_R \,.\, P_{si}} \cdot \frac{G_R\,(P_{ni} + P_{nri})}{P_{ni}}$$

$$\Rightarrow \quad F = \left[1 + \frac{P_{nri}}{P_{ni}}\right] \qquad \text{...(11.11)}$$

where P_{si} = Input signal power

P_{so} = Output signal power

P_{ni} = Input noise power

P_{no} = Output noise power

G_R = Power gain of the receiver

P_{nri} = Noise power generated at the receiver input.

We have $\dfrac{P_{nri}}{P_{ni}} = (F - 1)$

$$\Rightarrow \quad P_{nri} = P_{ni}\,(F - 1)$$

$$P_{nri} = KT_0B\,(F - 1) \qquad \text{...(11.12)}$$

KT_0B = Noise input power of receiver

K = Boltzmann constant

$= 1.38 \times 10^{-23}$ J/°K.

T_0 = Standard ambient temperature

$= 290$°K.

B = Bandwidth of the receiver.

The minimum receivable signal power for the receiver is equal to the equivalent noise power at the receiver input. If we may substitute for $P_{R\,min} = KT_0B(F-1)$ in Eq. (11.9) we obtain

$$d_{max} = \left[\frac{P_t S A_0^2 k^2}{4\pi K T_0 B\,(F-1)\,\lambda^2}\right]^{1/4} \qquad \text{...(11.13)}$$

Eq. (11.13) is fairly accurate in predicting the maximum radar range, provided a number of factors are considered. Among these factors are system losses, antenna imperfections, receiver non-linearities, operator errors, anamolous propagation etc.

It is possible to simplify Eq. (11.13) by substituting for various constants and substituting $kA_0 = 0.65\pi D^2/4$ and expressing the maximum range in nautical miles (1 n. mile = 1853 m).

$$d_{max} = 26\left[\frac{P_T D^4 S}{B\,\lambda^2\,(F-1)}\right]^{1/4} \qquad \text{...(11.14)}$$

where d_{max} = maximum radar range (in nautical miles)

P_T = Peak power transmitted

D = Antenna diameter, metres

S = Effective cross-sectional area of the target, m^2

B = Receiver bandwidth, Hz

λ = Wavelength, m

F = Noise figure (ratio).

11.5. Powers and Frequencies Used in Radar

The output of a radar transmitter is expressed in terms of *Peak Power*. This is the power which will be generated if the transmitter operates continuously at the power level represented by the pulses. Typical values of radar power lie within the range 100—500 kW though lower and higher values find use in particular cases.

Duty cycle is the fraction of time the radar is generating pulse power, it is given as

Duty cycle = Pulse repetition frequency × Pulse width

and Average power = Peak power × Duty cycle.

For example, in one second, a radar producing 2 μ sec pulses at a rate of 500 per second is 'ON' for

$$2 \times 10^{-6} \times 500 = 0.001 \text{ sec.}$$

∴ Duty cycle is 0.001 and if peak power were 400 kW, the average power is 400 watts.

Frequency range of most of the radar equipments is 100 to 25,000 Mc, with concentrations in a few bands in 1000 to 10,000 Mc range. These bands are commonly identified by letter—*L*, *S*, *X* etc. as defined in chapter 1.

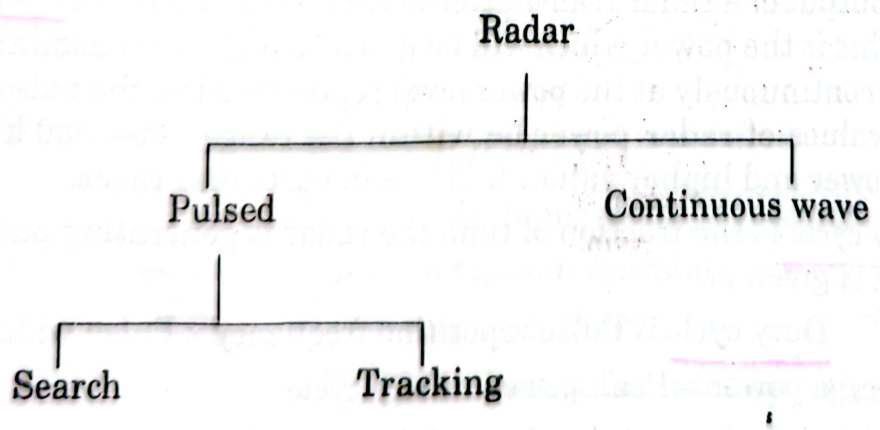
Long range radars usually operate in *S* and *L*-bands, with some use of *P* band too for the same purpose. Most airborne radars, and for that matter, all the radars designed for high resolution in bearing and range operate in the frequency range of 2,500—0,000 Mc. This allows the generation of narrow, high gain antenna patterns with moderate antenna structures-sizes.

The various frequency bands could be tabulated as below :

Band	*Frequency range GHz*	*Wavelength in cm*
P	0.22 - 0.39	77 - 133
L	0.39 - 1.55	19 - 77
S	1.55 - 5.20	5.8 - 19
C	3.9 - 6.9	4.8 - 7.7
X	5.2 - 10.9	2.7 - 5.8
K	10.9 - 36	0.83 - 2.7

C band is formed as an overlap of *S* and *X* bands

11.6. Types of Radar



We will study the various types of radars in more details in the following sections.

11.7. Basic Pulsed Radar System

A detailed block representation of a pulsed radar set is as shown in Fig. 11.2.

The trigger source gives pulses to the modulator which provides rectangular voltage pulses used as supply voltage for the output tube, thus switching it ON and OFF as required. This output tube can be a *Magnetron Oscillator* or a *Multicavity Klystron Amplifier.* In case of the amplifier, a source of microwaves is required whose output is amplified by the klystron. The transmitter part of the radar is terminated with the duplexer which allows high powered output pulses to the antenna for radiation.

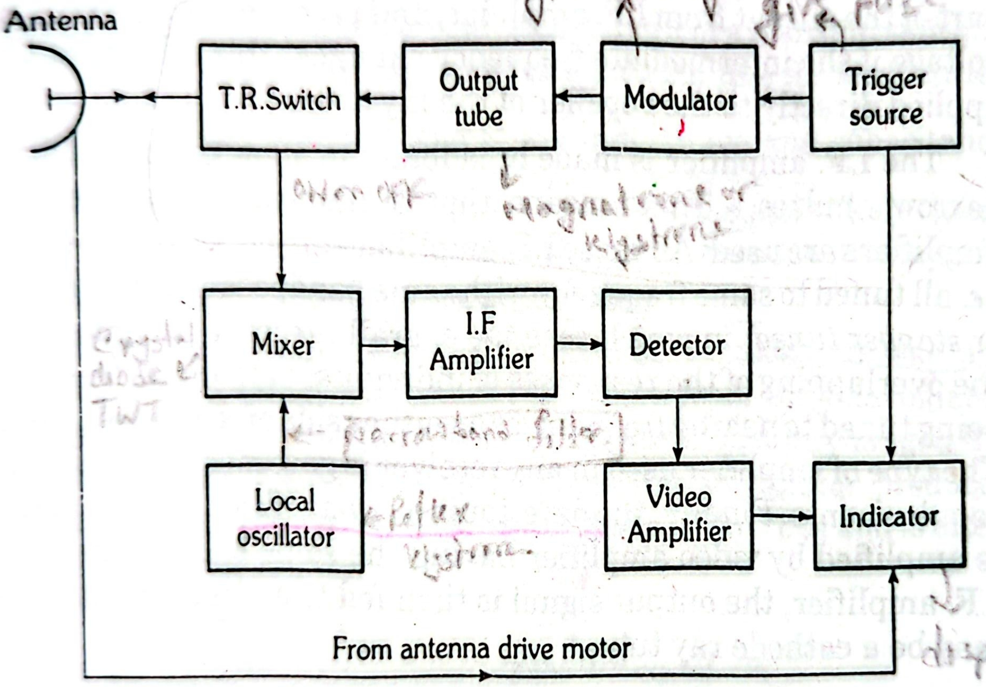

give rectangular
give pulse
Antenna
T.R.Switch
Output tube
Modulator
Trigger source
ON or OFF
magnetrons or klystrons
→ Transmi
Crystal diode & TWT
Mixer
I.F Amplifier
Detector
narrow band filter
Local oscillator
reflex klystron
Video Amplifier
Indicator
From antenna drive motor
display unit as cathode ray tube

Fig. 11.2. Pulsed Radar System—Block Diagram.

The receiver section is connected to the antenna at appropriate times by the duplexer. The receiver section of a radar set consists of a mixer, an I.F. amplifier stage and a detector followed by a Video Amplifier Stage whose output is fed to an indicator. The mixer is a crystal diode having a fairly low noise figure, but also a conversion loss. An R.F. amplifier can also be used which is mostly a low noise travelling wave tube. A better noise figure for the receiver is hence, achieved at the expense of extra bulk and complexity. T.W.T. has the further advantage of saturating for large signals and hence acts as a limiter that prevents burning of crystal as a result of strong echoes coming from nearby targets. The I.F. amplifier operates at 30 or 60 MHz or at a nearby frequency. If a crystal mixer is the first stage, the I.F. amplifier should be a low noise device to ensure that the overall noise figure of the receiver does not deteriorate to a great extent ; triode or transistor amplifiers are preferred and used quite commonly in cascade connection as they remove the need for neutralisation. Another source of noise in the receivers section of a radar is the local oscillator, which for microwave receivers is more generally a reflex klystron, which is a noisy device with a low efficiency. In order to reduce this noise due to this reflex klystron oscillator, it is customary to connect a narrowband filter between local oscillator and mixer to reduce noise band width of the osicllator; but in case of receivers employing A.F.C. (Automatic Frequency Control), this arrangement is unsatisfactory and a balanced mixer is used instead. If A.F.C. is used in the receiver section, it may simply consists of a phase discriminator, which takes part of the output from I.F. amplifier, and produces a d.c. correcting voltage if the intermediate frequency changes ; this voltage is then applied directly to the repeller of the klystron.

The I.F. amplifier is made broadband to allow the use of fairly narrow pulses. This means that a number of cascaded I.F. amplifiers are used. All these I.F. amplifiers are either *synchronous, i.e.* all tuned to same frequency with same bandpass characteristics, or *stagger tuned,* in which case the overall response is achieved by the overlapping of the responses of individual amplifiers, the latter being tuned to nearby frequencies on either side of centre frequency. The type of amplifier used in any receiver is governed by the specific requirements. Finally, the detector is a crystal diode, whose output is amplified by video amplifier having the same bandwidth as the I.F. amplifier, the output signal is then fed to a display unit which may be a cathode ray tube.

11.8. Modulators

In a radar transmitter, the modulator is a circuit arrangement whose function is to generate a pulse of appropriate amplitude, length and repetition rate, to be applied between anode and cathode of the power tube of radar transmitter. The power requirements may be pretty high. For example, a 500 kW radar set operating on 25% efficiency will require a modulator capable of supplying 2000 kW peak power to power tube.

Two types of modulators are in common use : A line pulser and a hard tube or driver power amplifier pulser.

The line pulsing modulator corresponds to the high level modulator used for amplitude modulation ; in that the anode of magnetron or collector of a multicavity klystron, is modulated straight away by a system that generates and provides them with large pulses of supply voltage. This can be achieved by slowly charging and then suddenly discharging a transmission line. We can easily show that if a transmission line is charged to a voltage V, then discharged through a load whose impedance equals the characteristic impedance of the transmission line, a voltage of $V/2$ be maintained across this load for a time $2T$, where T is the time taken by the electromagnetic wave to travel from one end of transmission line to the other end.

In case the pulse duration ($2T$) is to be 1 μ sec, the line length is to be almost 500 ft, which is too long for convenience ; use is therefore made of a Pulse Forming Network (PFN). Fig. 11.3 illustrates a very basic line modulator, also we can see that PFN simply looks identical to the equivalent circuit of a transmission line and behaves exactly similar to a transmission line for frequencies below $f = \frac{1}{\pi\sqrt{LC}}$, where L and C are inductance and capacitance respectively per section. In high power radars, the most likely choice of device for a switch is a hydrogen thyratron because it is capable of switching very rapidly, very high powers.

Simplicity, compactness and efficient working are the advantages of the line modulators ; it suffers from the unavoidable disadvantage that the pulse forming network must be changed if a different pulse length is required. This line modulator produces pulses that have adequately vertical sides and flat tops and is often used in practice.

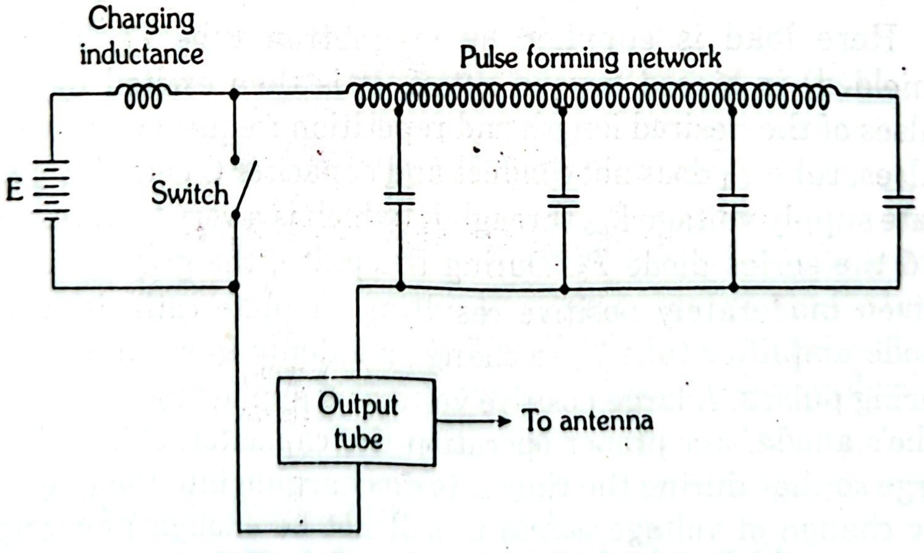
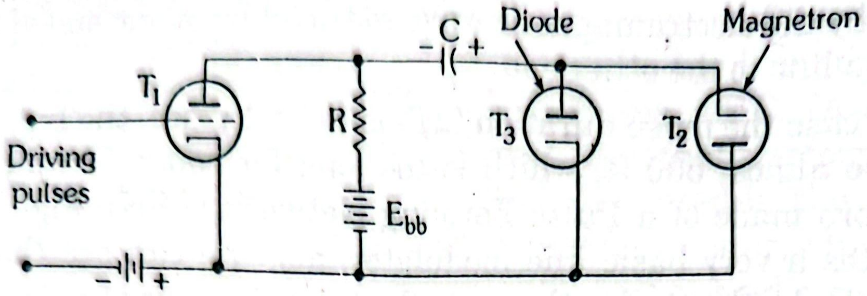
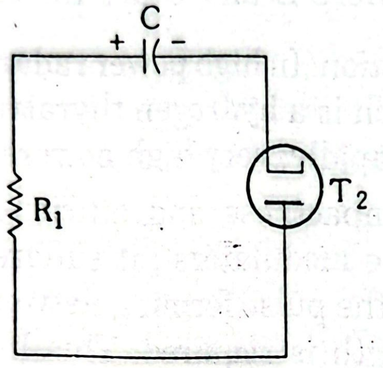


Fig. 11.3. Simple line pulser using pulse forming network.

The *driver power amplifier* or *hard tube* modulator also provides high level modulation of the output tube, but here the pulses are generated at a low level and then amplified. The driver is very often a blocking oscillator which is triggered by the timing circuit and drives a high power vacuum tube amplifier, such as a shielded-grid triode, which in turn provides large pulses for the output tube. **Fig. 11.4** below shows the actual circuit and the equivalent circuit during pulse of a **Hard Tube Pulser.**



(*a*) Actual circuit



(*b*) Equivalent circuit during pulse.
Fig. 11.4. Hard tube pulser.

Here load is supplied by magnetron tube T_2. The triode (shielded) is biased beyond cutoff. It is then excited by positive pulses of the desired length and repetition frequency. Between the pulses, tube T_1 does not conduct and capacitor C gets charged upto plate supply voltage E_{bb} through R (which is a very high resistance) and the series diode T_3. During the pulse, the grid of tube T_1 is driven moderately positive resulting in plate cathode circuit of triode amplifier tube T_1 to change suddenly from an open circuit during pulses. A large positive voltage is applied to the magnetron tube's anode. For proper operation the capacitor, C is sufficiently large so that during the time it is discharging into the magnetron, the change of voltage across C will not be enough to change appreciably the frequency and power output of the magnetron.

The hard tube pulser overcomes the disadvantage which is apparent with the line modulator, pulse length in this case can be easily adjusted by merely changing the length of the driving pulse. Hard tube pulser is also more suitable for generating multiple or coded pulses. The disadvantage associated with hardtube pulser is that it is bulkier and more expensive. This is because the total energy that must be stored in the capacitor is much greater than the energy of a single pulse. In addition, the vacuum tube (switching) has a higher voltage drop and hence consumes more power than the thyratron tube used for a line pulser.

Often a pulse transformer is used to couple the modulator to the load impedance. Fig. 11.5 illustrates a simple arrangement applied to the line pulser ; a similar arrangement could also be used for a hard tube pulser.

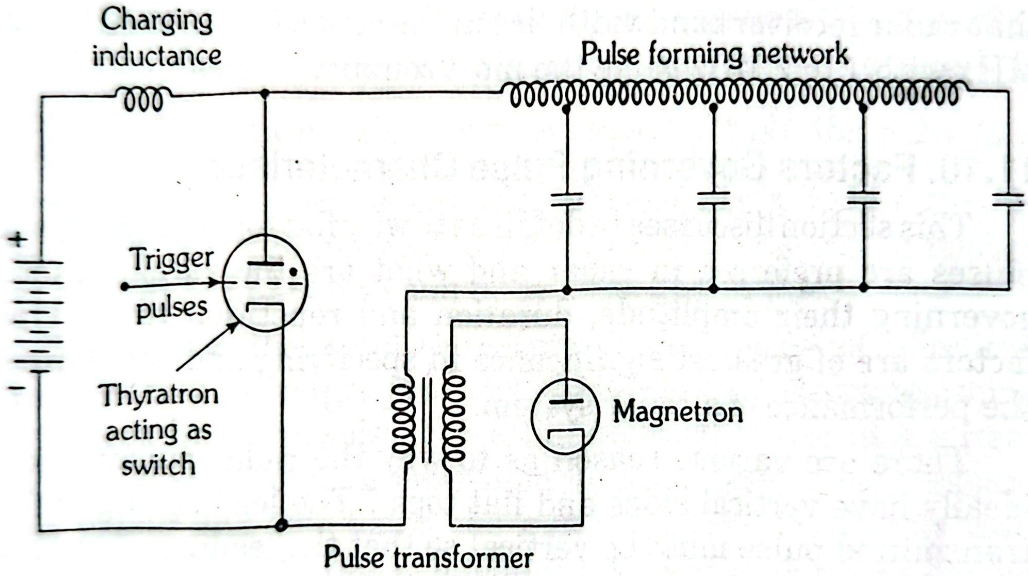


Fig. 11.5. Line pulser with pulse transformer.

The pulse transformer must be designed so that the shape of the pulse doesn't change and must be so proportioned that it can with stand high power and high voltage without core saturation or insulation breakdown. Use of pulse transformer provides flexibility is design and use of a modulator.

11.9. Receiver Bandwidth Requirements

We know that the receiver frequency response is governed by the width of pulses which it is required to receive. The narrower the pulses, greater is the IF and the video bandwidth required whereas the RF bandwidth is normally greater than this. With a given pulse duration T, the receiver bandwidth varies depending on the number of harmonics of the pulse repetition frequency that are needed to provide a received pulse having a suitable shape. Hence if vertical pulse sides are required for the pulses, in order to give a high/fair degree of resolution, a large bandwidth is required. Moreover bandwidth has to be increased if more information about the target is required (according to Information Theory), but very large bandwidth reduces the maximum range of the radar by admitting more noise as is clear from Eq. (11.13) which shows that the maximum range is inversely proportional to fourth root of the bandwidth.

The IF bandwidth of a radar receiver is n/T, where T is the pulse duration and n is a number whose value ranges from 1 to 10, depending on the circumstances, $n = 1$ to 1.4 are most commonly used.

Since pulse widths usually range from 0.1 to 10 μ sec, we see that radar receiver bandwidth lies in the range from 200 KHz to 10 MHz with 1 to 2 MHz being the most common values.

11.10. Factors Governing Pulse Characteristic

This section discusses in detail as to why flat topped rectangular pulses are preferred in radar and what are the various factors governing their amplitude, duration and repetition rate ; these factors are of greatest significance in specifying and determining the performance of a radar system.

There are various reason as to why the radar pulses should ideally have vertical sides and flat tops ? The leading edge of the transmitted pulse must be vertical so that the leading edge of the received pulse is also as nearly vertical.

If the leading edge of received pulse is not vertical, ambiguity may exist about the precise instant at which the pulse has been returned and may result in inaccuracies as to the exact measurement of target range. This precision is particularly desirable in case of fire control radars.

Flat top pulses are essentially required to be applied to the magnetron anode otherwise its frequency is pushed, and also because the efficiency of magnetron or multicavity klystron falls remarkably if the supply voltage is reduced.

A steep trailing edge is necessary for the transmitted pulse so that the duplexer can switch the receiver over to the antenna as soon as the pulse has passed out. This immediate transition of duplexer from transmitter to receiver will not take place if the pulse decays slowly, since then there will be sufficient pulse power present to keep the TR switch ionised. Keeping in mind that the energy transmitted during the decay of a pulse does not contribute much to the total transmitted power, we find that a pulse which has a trailing edge that is not steep has the effect of lengthening the period of time during which the receiver is disconnected from the antenna, and this further causes a limit on the minimum range of the radar.

There are two factors governing the pulse repetition frequency or P.R.F. The first of these factors is the maximum range required, as it is necessary not only to be able to detect pulses returning from distant targets, but also to allow them time to return before the transmission of the next pulse. For example, if a given radar has a range of 25 nautical miles, at least 310 μ sec must be allowed between successive pulses—the period being known as **Pulse Interval**. Failure to do so will result in ambiguities. For example, if pulse interval is only 250 μ sec an echo received 60 μ sec after transmission of pulse could mean either that the target is $\frac{60}{12.4} = 4.85$ nautical miles away or possibly that the pulse is a reflection of the previously sent pulse from a target that is $(250 + 60)/12.4 = 25$ nautical miles away. This discussion implies that the pulse interval should be as large as possible.

But on the other hand, the greater is the number of reflections of pulses from the target, greater is the possibility of distinguishing the target from the noise. Since the antenna moves at a certain speed in many radars, a lower limit on pulse repetition frequency fixed exists and this limits the pulse interval. Commonly used values of P.R.F. are 200 to 10,000 per second with corresponding pulse interval as 100 to 5000 μsec and hence maximum range is limited to 8 to 400 nautical miles. However in case of distant targets *viz.*, satellite or space probes etc., lower values of P.R.F. are used (as low as 30 pulses/sec).

If the minimum range is required to be short, then short pulses must be transmitted which is another argument in favour of a perfectly vertical trailing edge for the transmitted pulse. During the duration of pulse being transmitted, the receiver is disconnected from the antennas (in radars using duplexers), thus it is clear that the echoes returned during this period cannot be received. Suppose the pulse duration is 2 μsec, then no echoes can be received during this period, *i.e.* no echoes can be received from targets closer than 985 ft. and this is the *minimum range of the radar.*

Another factor that favours the pulses of short duration is that use of short pulses improves resolution, *i.e.* range resolution which is the ability to distinguish between targets whose distance from the transmitter differs only slightly. If a pulse duration of 1 μsec is used, this means that echoes returning from separate targets that are 1 μsec distant (*i.e.* about 500 ft. apart), will mix into one returned pulse and will not be separated. Thus we see that in the present case, maximum range resolution is 500 ft.

Now we proceed on to look for some points in favour of longer pulse durations. The most important of these is that as the pulses are made shorter the bandwidth of the receiver must be increased and Eq.(11.12) shows that this tends to increase noise and hence decreases the maximum range. Also maximum range is inversely proportional to the bandwidth. This defect can however be out-eracted by increasing the peak pulse power, but only at the by higher cost, size and power consumption. In fact, the maximum range depends on *peak energy* rather than *peak power*. Since one of the terms in Eq. (11.14) is P_T/B and also bandwidth B is inversely proportional to the pulse duration, we can as well say that maximum radar range depends on the product ($P_T \times T$) and this product equals pulse energy. On the other hand, we must keep in mind that when we are increasing pulse width with a constant value of P.R.F., we are increasing the duty cycle as well ; hence an increase in average power is taking place. Duty cycle is nothing but the fraction of time duration during which the output tube is *ON*. *e.g.* if P.R.F.=1000 and pulse width is 1.5 μsec the period of time actually accupied for transmission of pulses is 1000 × 1.5 = 1500 μsec/sec = 0.0018 or 0.18%. Increase in duty cycle results in an increase in dissipation of output tube ; it may also have the effect of causing a reduction in peak power because peak power and average power are closely related for any tube. If large duty cycles are required, it is worth while to use travelling wave tube for the purpose.

11.11. Duplexer

A duplexer is a circuit designed to allow the use of same antenna for both transmission and reception with minimum interference between the receiver and the transmitter. It utilises of fast acting radio frequency switches known as *TR (transmit receive) block*, and *anti-transmit receive (ATR) block* which are operated using energy from the transmitted pulse. Duplexes protects the sensitive receiver from the damaging effect of high energy of the transmitter.

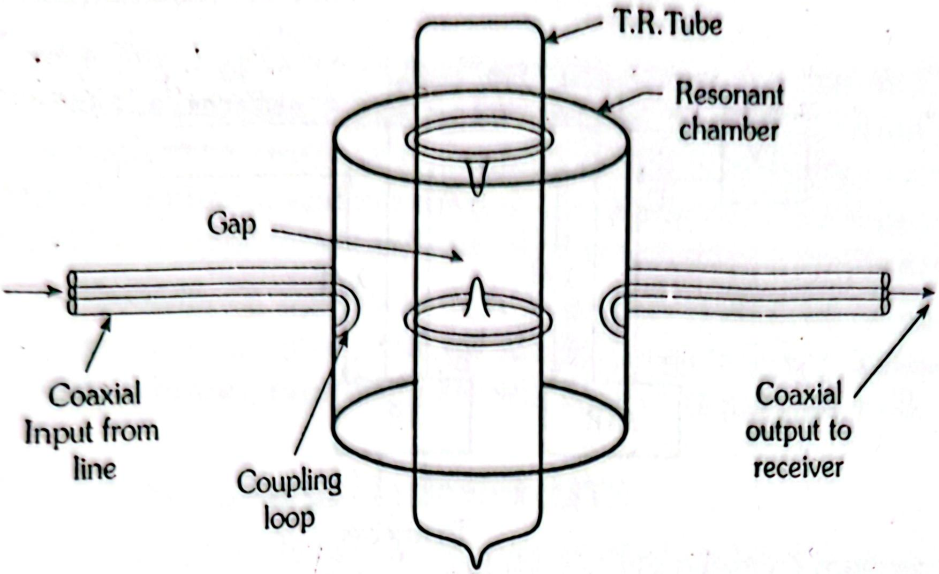
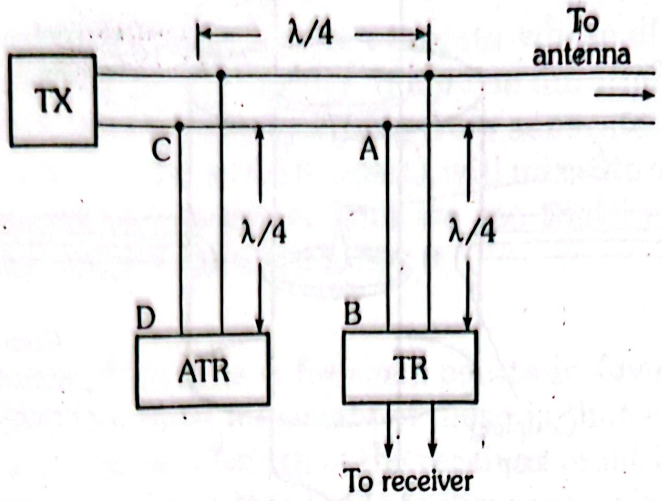


Fig. 11.6. Typical TR tube and cavity to be used with a co-axial transmission system.

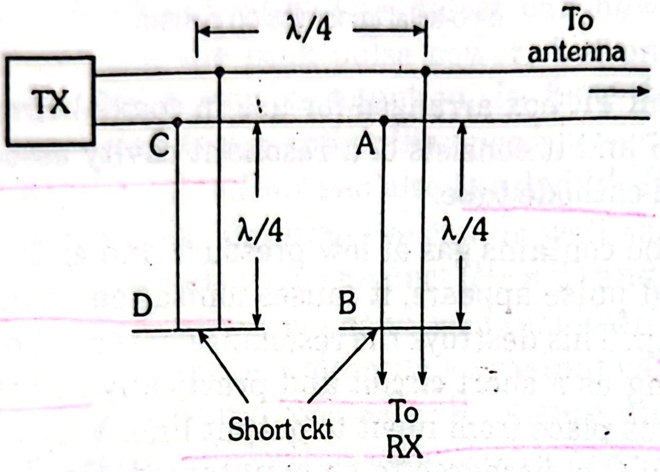
A typical TR box arranged for use in coaxial circuits is shown in Fig. 11.6 and it consists of a resonant cavity associated with a special cold cathode tube.

The tube contains gas at low pressure and as the high energy transmitted pulse appears, it causes ionisation across the narrow internal gap. This destroys the resonance in the TR box which now starts acting as a short circuit and practically no transmission of energy takes place from input to output line. Very little energy is required by the discharge to be maintained. On the other hand, when the gas tube is not ionised cavity resonance enables energy transfer, easily through the cavity. Similar units are used with waveguide systems with the difference that coupling loops are replaced by **Windows** (See Chapter 5 on Component), which match the cavity to the impedance of the guide.

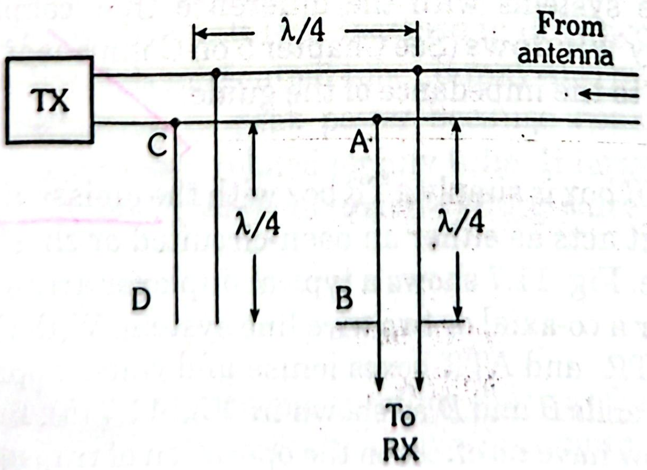
An ATR box is simply a TR box with the omission of output lead. Normally it acts as either an open-circuited or short circuited load impedance. Fig. 11.7 shows a typical duplexer arrangement for use with either a co-axial or two wire line system. With the transmitter ON, both TR and ATR boxes ionise and cause approximate short circuits at ends *B* and *D* as shown in Fig. 11.7 (*b*). Branch lines *AB* and *CD* now have no effect on the operation of transmitter, because both are $\lambda/4$ long and short circuits at ends *B* and *D* correspond to open circuits at *A* and *C*, *i.e.* an extremely high impedance shunted across the line. At the same time, since the TR box approximates short circuit at *B*, it prevents whatever little energy reaches *B* from reaching the receiver and hence serves to isolate the receiver from the antenna when the transmitter is ON.


λ/4
To
antenna
TX
C
A
λ/4
λ/4
D
B
ATR
TR
To receiver

(*a*) Layout of Duplexer system.


λ/4
To
antenna
TX
C
A
λ/4
λ/4
D
B
Short ckt
To
RX

(*b*) Conditions during transmission of pulse.


λ/4
From
antenna
TX
C
A
λ/4
λ/4
D
B
To
RX

(*c*) Equivalent circuit when transmitter in inoperative.

Fig. 11.7.

At the end of the pulse, the TR and ATR boxes deionise very rapidly and become open circuits as is shown by the equivalent circuit of Fig. 11.7 (*c*). The open circuit at *D*, causes the presence of a very low impedance (≈ short circuit) across the line at C which causes the impedance looking toward the transmitter from A to be very high. As a result, a major part of the echo energy coming in from the antenna and reaching A travels toward the receiver and thus the transmitter gets effectively disconnected from the antenna.

If broadband operation of a duplexer is desired, a balanced duplexer may be used; but for single frequency applications the described branch type duplexer will serve the purpose well.

11.12. Moving Target Indicator (MTI)

It is not possible for an observer to distinguish a moving target in the presence of permanent echoes of comparable appearance on a radar representation or a radar indicator. Another difficult situation arises if the moving target has a range and bearing such that the echo from the moving target gets superimposed on the ground clutter. This situation is particularly troublesome in mountainous regions and in the near vicinity of cities. A moving target indicator radar depends on Doppler's principle for its basic operation.

Doppler effect. The relation at the radar, between the phase of the transmitted pulse and the phase of the resulting echo from a fixed target is same for successive pulses. Doppler's effect is responsible for change in the pitch of whistle from a passing train and is as well used in making a *moving target indicator radar*. The relative phase of echo signals received from a moving target continuously change with respect to the phase of the transmitted pulse, when there is a continuous change in distance of the target.

It can be easily shown that if the relative velocity of two objects is $+v_r$ and if this is much smaller than the velocity of light, v_c, then frequency f_t transmitted from one body to the other will be changed to $(f_t + f_d')$, where f_d' is the Doppler frequency and is given by

$$f_d' = f_t \frac{v_r}{v_c} \quad \text{...(11.15)}$$

In radar, a signal undergoes f_d' change in frequency on arrival at the target and then again there is a change in the frequency on its return to the radar set and hence the overall effect is double. Therefore, Doppler's frequency, f_D for the radar is

$$f_D = 2 . f_t \frac{v_r}{v_c} \quad \text{...(11.16)}$$

$$= \frac{2v_r}{\lambda} \quad \text{...(11.16a)}$$

Since $f_r/v_c = \frac{1}{\lambda}$

where λ = transmitted wavelength.

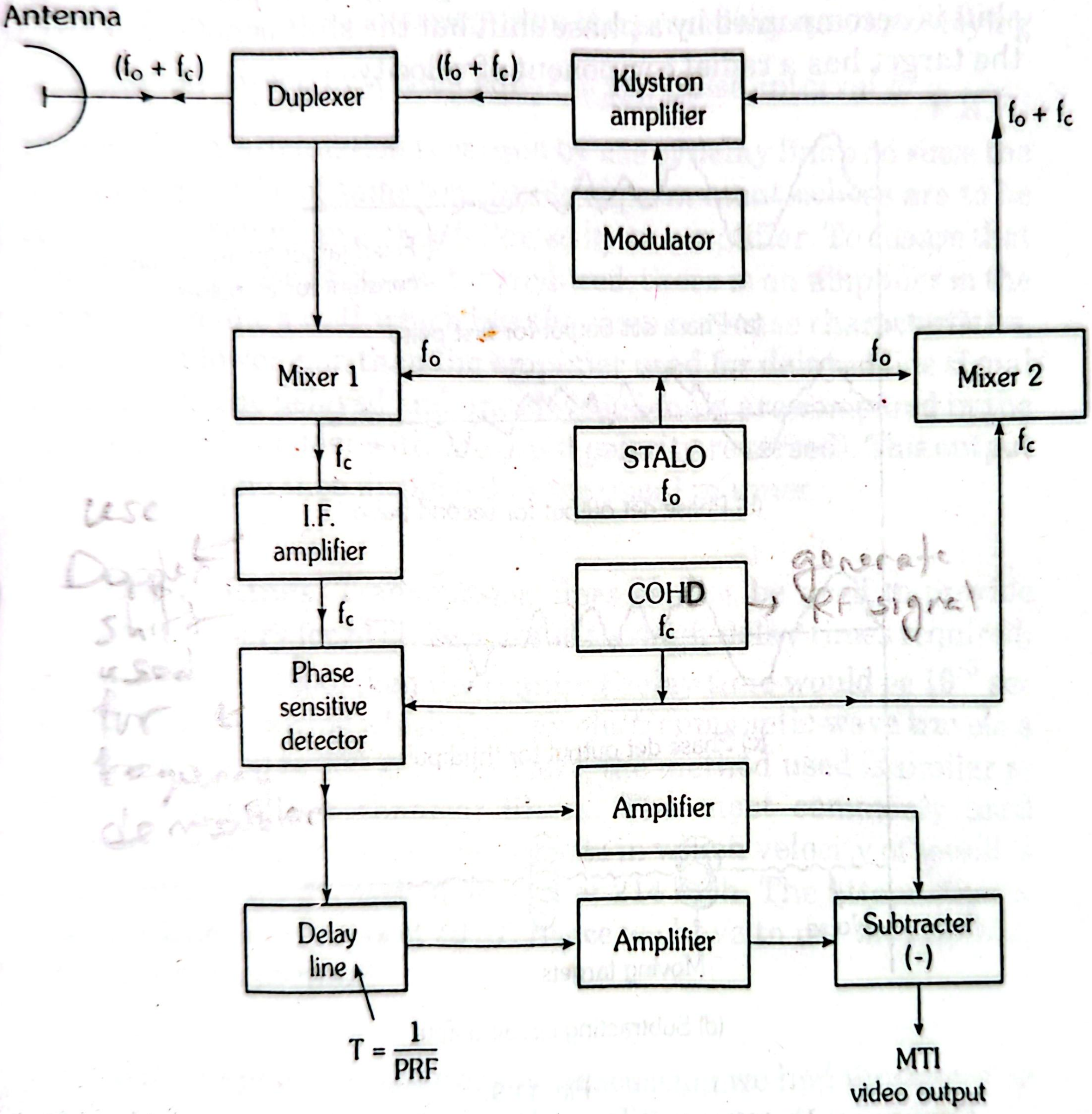
On the basis of this change in frequency, it is possible to calculate the relative velocity of the target with the pulsed or continuous wave (CW) radar. It is also possible to distinguish between moving and stationary objects and to eliminate the blips due to stationary targets with pulsed radar.

Basically the moving target indicator system compares a set of received echoes with those received during the previous sweep and cancels out those whose phase has remained unchanged. This applies to echoes due to stationary objects but those due to moving targets undergo a phase change and are, hence, not cancelled. Since the clutter due to stationary target is removed, it permits not only easier determination of moving targets but also a reduction in the time taken by an operator to *take in* the display and besides that it allows the detection of moving targets whose echoes are hundreds of times smaller than those of nearby stationary targets and those which would have been otherwise masked by the stationary objects nearby. MTI can be used with a radar using a power oscillator, *i.e.* magnetron output but it is more convenient with the one whose output tube is a power amplifier, *i.e.* a klystron. In the present discussion we discuss the one with output tube being power amplifier.

Fig. 11.8 shows a block diagram representation of a moving target indicator radar. It consists of a duplexer, or a simple circulator arrangement could as well be used. It connects antenna to the receiver section and the transmitter sections at proper instant of time.

The transmitted frequency in the Fig. 11.8 is the sum of outputs of two oscillators produced in second mixer—**Mixer 2.** The two oscillators are : **Stalo** or **Stable** local oscillator and the second is **Coho** or **Coherent** oscillator, which operates at the same frequency as intermediate frequency and provides coherent signal whose use will be discussed later.

Mixers 1 and 2 are identical and both use the same local oscillator (the Stalo) and thus the phase relationship existing in their inputs is preserved in their outputs. This makes possible the use of Doppler's shift at the IF stage, instead of the less convenient RF ($f_o + f_c$) stage, where f_o is frequency of Stalo and f_c is frequency of **Coho**. The output of the IF amplifier and a reference signal from the **Coho** are fed to a phase sensitive detector which is a circuit that is very much similar to phase discriminator (a detector used for frequency demodulation).


Antenna
$(f_o + f_c)$
Duplexer
$(f_o + f_c)$
Klystron amplifier
$f_o + f_c$
Modulator
Mixer 1
f_o
f_o
Mixer 2
f_c
STALO f_o
f_c
I.F. amplifier
COHD f_c
f_c
Phase sensitive detector
Amplifier
Delay line
Amplifier
Subtracter (-)
$T = \frac{1}{PRF}$
MTI video output

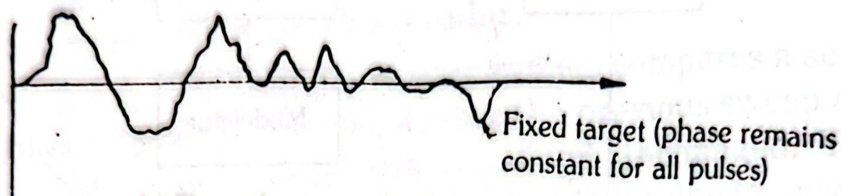
use Doppler shift used for frequency demodulation

generate RF signal

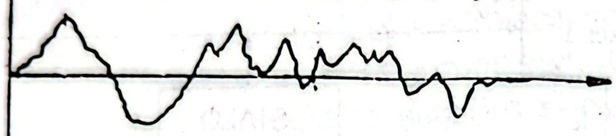
Fig. 11.8. Block diagram of MTI radar.

Since **Coho**-(Coherent oscillator) is used for the generation of RF signal as well as for reference in the phase detector and also the mixers do not introduce differing phase shifts, thus the transmitted and reference signals are locked in phase and are said to be

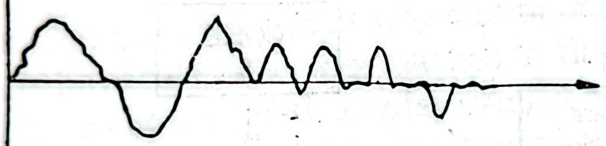
Coherent, hence the name **Coho**. Since the output of this detector is phase sensitive, an output is obtained for all fixed or moving targets. However the phase difference between transmitted and received signals is constant for fixed targets, whereas it varies for moving targets. Doppler frequency shift is responsible for this variation of phase difference for moving targets. Doppler frequency shift is accompanied by a phase shift but the shift is not constant if the target has a radial component of velocity.



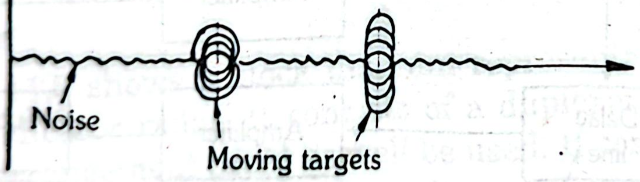
(a) Phase det output for first pulse



(b) Phase det output for second pulse



(c) Phase det output for third pulse



(d) Subtracting circuit output

Fig. 11.9.

For example, if the Doppler frequency is 1000 Hz and the return time for a pulse is say 26 μsec, (that is equivalent to 5 nautical miles the phase difference between the transmitted and received signals will be some value ϕ, which is the same as for a stationary target at that point, *i.e.* $\phi + \frac{1000}{62} = 16.12$ complete cycles or $16.12 \times 2\pi = 101.4$ rad. When the next pulse is returned from the moving target, the latter will now be closer say 61 μsec away, giving a phase shift of $101.4 \times \frac{61}{62} = 99.7$ radians. Thus the phase shift is definitely not constant for moving targets. This situation may be

P.R.F = pulse repitition frequency

illustrated graphically for a number of successive sweeps in Fig. 11.9.

Fig. 11.9 illustrates that those parts of each sweep that correspond to stationary targets are identical with each sweep but the portions corresponding to moving targets keep changing in phase. Thus we subtract each sweep from the preceding one, by delaying the earlier sweep by a time equal to the pulse interval or $\frac{1}{\text{P.R.F.}}$. Since heavy attenuation is caused by use of delay line and since the signals must be of same amplitude if permanent echoes are to be cancelled, delay line is thus followed by an amplifier. To ensure that a spurious phase shift is not introduced, there is an amplifier in the undelayed line a well, which has the same response characteristics, but much lower gain than the amplifier used for delayed line signal amplifier. The delayed and undelayed signals are compared in the subtractor (*i.e.* adder with one input polarity reversed). This output is rectified and then displayed in the usual manner.

Delay Lines. Transmission lines cannot be used to provide delay necessary for MTI, because of the high delay times required. If the P.R.F is 1000, then the required delay time would be 10^{-3} sec or 1000 μsec, during which time an electromagnetic wave travels a distance equal to 300 km. Therefore, the method used is similar to that used with mechanical filters. The most commonly used material for delay line is fused quartz in which velocity of sound is 0.544 cm/μsec = a length of 544 cm or 214 inch. The attenuation of such a line is in excess of 40 dB hence we have to use an amplifier stage for the purpose.

Blind speeds. In the previous discussion we had illustrated as to the fact that there was a phase difference of 101.4-99.7=1.7 radians between successive sweeps. If the target has a velocity whose radial velocity component results in a phase difference of exactly 2π radians between successive sweeps this is equivalent to saying as to having no phase shift at all and thus the target appears stationary and echoes from it get cancelled on the MTI. A speed corresponding to this is called blind speed, as are any integral multiples of this speed. However, the problem is not so serious and does not stay beyond a small number of sweeps, unless the target is flying directly at the radar set with a constant velocity. This is unlikely unless, of course, the target knows the blind speed precisely, in which case solution is to use a P.R.F. that is variable in a predetermined fashion, hence overcoming the difficulty arising due to blind speed.

11.13. Tracking Radar Systems and Search Radar System

As a result of the discussions so far, we have been able to see that a radar system is generally required to perform one of the two tasks : it must either search for targets or else track them once they have been pinpointed. Sometimes one radar performs both functions, whereas in other installations two separate radars are used. Each of these two broad groups can be further sub-divided depending on the specific application and now we will describe the most common of these.

Search radar systems. So far we have come across a general block diagram of search radar system and the antenna scanning methods and display systems are to be discussed in the coming sections. Thus we see that such a radar system must search a target in a large volume of space regardless of whether its presence is known or not ; to do this, the radar should be capable of scanning its region rapidly. Thus the narrow beam is not the best antenna pattern for this purpose, because it would take too long to scan a given region. Once the approximate bearing of the target is known with a broad beam, the information is passed over to a tracking radar, which quickly acquires and then follows the target.

An alternative solution to the problem consists in using two fan shaped beams, obtainable from a pair of connected cut paraboloids, oriented so that one moves in azimuth and the other moves in elevation. The two rotate together using helical scan so that while one searches in azimuth, the other antenna acts as a height finder and a large area is thus covered rapidly. The common type of radar using this principle is the air traffic control radar used both at civilian as well as military airports.

If the area to be scanned is small, a pencil beam and spiral scanning can be used to advantage along with plan position indicator, *i.e.* P.P.I. unit. Weather radar and air borne navigation radars are examples of this type. Marine navigation and ship to ship radars are of a similar type, with an exception in that the scan here is of horizontal type with a fan-shaped beam.

Distant early warming (DEW) and aircraft surveillance radars are also acquisition radars with a limited search region, but they differ *from* the other types, in that they work at ultra-high frequencies and are characterised by huge powers as well a huge antennas.

Azmuth: Angle between north pole & altitude

Tracking radar system or automatic tracking radar. A radar is sometimes arranged so that its antenna is continuously pointed in the direction of a target, while at the same time, a **Range Gate** follows the same target and provides continuous information about range etc. Such an automatic tracking system can be used to aim guns, provide continuous data about plotting etc.

Tracking both in azimuth and elevation is easily obtained with a *conical scan*. For tracking in azimuth only, use is made of a simple lobe switching arrangement that shifts the position of the beam slightly in the horizontal plane. The difference in the strengths of the returned signals for two lobe positions is then used as an error signal that controls a servo-mechanism, which in turn corrects the antenna position. Tracking in range is achieved by applying the output of the receiver to two gated amplifiers with their inputs paralleled. Gates on these amplifiers are synchronized with the transmitted pulses in a way, such that each gate opens for a few micro-seconds, at a definite and adjustable time interval after transmission of each pulse. The timing of two gates is so adjusted so as to give an overlap slightly less than a pulse length as shown in Fig. 11.10.

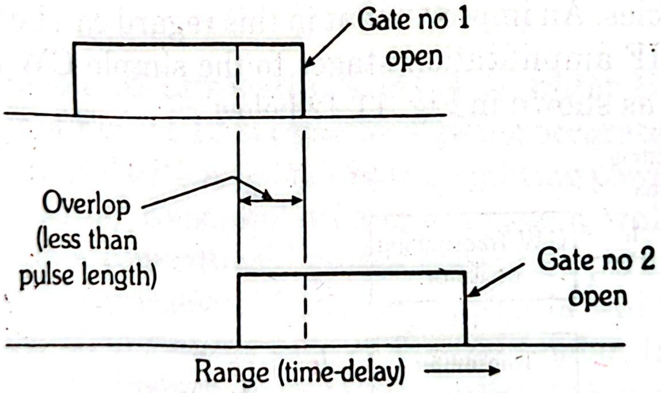


Fig. 11.10. Arrangement of gates used in range tracking.

If the returning pulses lie entirely in either one of the gates, the overlap portion corresponds to a range that is either slightly too small or slightly too large, whatever the case may be. The difference in the outputs of gates, therefore, an error signal which is used to readjust the range of the pair of gates so that the overlap of the two gates corresponds to a time delay that represents exact range of the target. Therefore, at the time of correct adjustment of the gates, equal output signal is produced by the two gated amplifiers and the time delay corresponding to this condition gives the actual range of the radar.

Continuous wave systems. Although most radar systems use energy radiated in the form of pulses, it is possible to detect moving targets by radiating unmodulated continuous wave energy. We have already studied that the Doppler effect can be used for relative speed measurement ; this gives rise to two radar systems that send out continuous sine waves rather than pulses as will be explained in the discussion that follows.

Doppler radar. A simple block diagram of Doppler CW (continuous wave) radar is shown in Fig. 11.11. It detects the frequency change due to a moving target and displays it as an equivalent velocity.

The circulator shown in the block diagram is used to provide necessary isolation between transmitter and receiver sections because the transmission is continuous. It is capable of isolation upto 30 dB. Some transmitter signal thus gets into the receiver section, and this after mixing with the incoming signal in the detector produces Doppler frequency. The latter is generally in the audio range and is amplified before being passed on to a frequency meter. Lack of sensitivity is the main disadvantage of a system as simple as this. The crystal diode detector that is used to accommodate the high incoming frequencies is not a very good device at the audio output frequency because of the modulation noise exhibited at low frequencies. An improvement in this regard can be made by adding certain IF amplification stages to the simple CW radar (Doppler) system, as shown in Fig. 11.12 below.

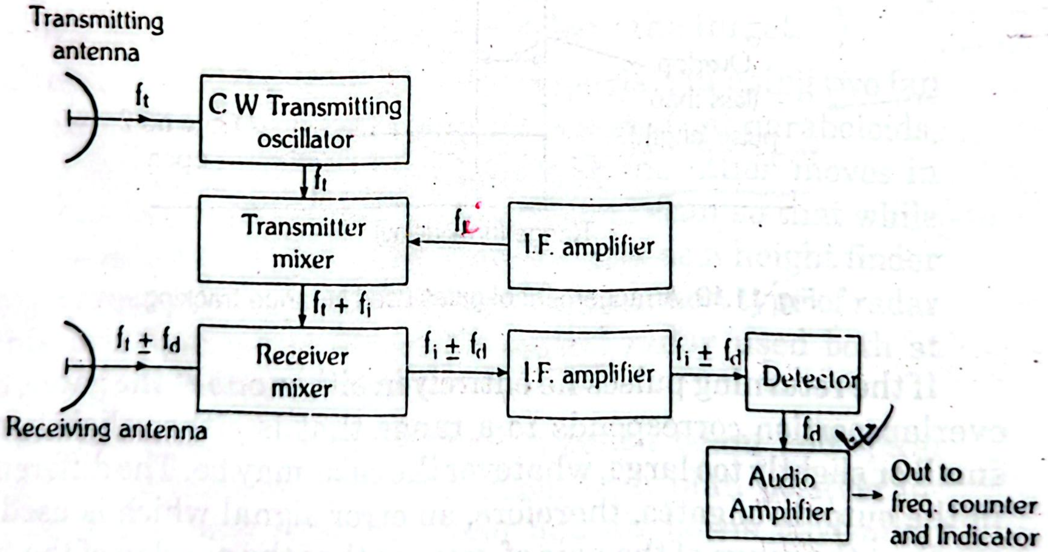

Transmitting antenna
f_t
C W Transmitting oscillator
f_t
Transmitter mixer
f_i
I.F. amplifier
$f_t + f_i$
$f_t \pm f_d$
Receiver mixer
Receiving antenna
$f_i \pm f_d$
I.F. amplifier
$f_i \pm f_d$
Detector
f_d
Audio Amplifier
Out to freq. counter and Indicator

Fig. 11.12. CW Doppler radar with IF amplification.

As shown in Fig. 11.12, a small part of the transmitter output and output of a local oscillator are mixed together and the sum is fed to the receiver mixer. Doppler shifted signal is also received from the receiver antenna and this produces an output difference frequency that is typically 30 MHz± Doppler frequency.

The output of this receiver mixer is amplified and demodulated again and the signal from the second detector is simply Doppler frequency without a ± sign preceding it, so that it is not possible to infer whether the target is approaching or receding. The overall receiver system is very much similar to superheterodyne system, and the extra sensitivity is provided by the lowered noise, since the output of the crystal diode mixer is now in the range of 30 MHz and at this frequency the modulation noise almost disappears.

Different receiving and transmitting antennas have been shown in the fig, but the arrangement is not compulsory. A circulator could alternately be used instead. Increased isolation between transmitter and receiver sections of the radar is provided by use of separate antennas, especially, since there is no longer any requirement need for a small portion of transmitter output to leak into the receiver mixer, as was required in the simpler model of Fig. 11.11. On the contrary, such leakage is very highly undesirable, because it degrades the receiver performance by bringing with it hum and noise from the transmitter. In fact, the transmitter output power is mainly influenced due to the problem of isolation. As a result CW power from such a radar system seldom exceeds 100 watts and is often lesser.

Advantages and Limitations of CW Doppler Radar. CW Doppler radar of Fig. 11.12 is capable of giving accurate measurements of relative velocities, using low transmitting powers, simple circuitry, low power consumption and equipment which is one-fourth in size of a conventional pulsed radar. It's performance is unaffected by the presence of stationary objects which are disregarded in the same manner as in MTI pulsed radar. In addition, it can theoretically operate down to zero range, because unlike in the pulsed systems, here the receiver is *on* at all times. It can also measure a large range of target velocities, quickly and accurately, with a high degree of efficiency. The CW radar with some additional circuitry, can even measure the direction of the target, along with its velocity.

There are some disadvantage as well associated with CW Doppler radar which still make pulse radar systems to be used in the majority of applications.

Firstly, it is limited in the maximum transmitted power which places a limit on its maximum range. Secondly, it is easily confused by the presence of a large number of targets. Finally, the Doppler radar is incapable of indicating the target range, which forms its greatest drawback. This is because the transmitted signal is unmodulated. Thus the incapability of Doppler CW radar in measuring the range of the target, limits its use to certain set applications only.

One of the main applications of CW Doppler radar is in aircraft navigation for speed measurement. Another application is in a *rate-of-climb* meter for vertical take of planes. Finally, perhaps the most common application is in radar speed meter used by the police.

Frequency-modulated CW Radar. The greatest drawback of Doppler CW radar (its inability to measure range) can be removed if the transmitted carrier is subjected to frequency-modulation.

Thus by employing frequency modulation, the inability of CW radar to distinguish one cycle from another can be overcome. Although use of FM will involve an increase in the bandwidth of the system, this will also enable more information (with regard to range) to be conveyed.

The airborne altimeter is a common example of an FM CW radar as shown in Fig. 11.13.

Any modulating waveform may be used but sawtooth provides simplicity. Since the object is stationary in case of an airborne altimeter, a frequency difference proportional to height of plane exists between the received and transmitted signal. This is because of the fact that, the signal received at a particular moment was sent at a time when instantaneous frequency was different, and if rate of change of frequency of signal due to FM process is known, the time difference between the transmitted and the received signals, as also the height can be easily computed. Hence the output of mixer shown in Fig.11.13 is amplified, limited, fed to a frequency counter and finally indicated on an indicator calibrated in feet. If the relative velocity of the radar with respect to the target is not zero, another frequency will be superimposed on the top of frequency difference discussed previously, this taking place due to Doppler frequency shift phenomenon. However, the average frequency difference remains constant, and due to the time difference between transmission and return of particular cycle of signal ; therefore, correct height measurements can still be made based on average frequency difference. The beat frequency superimposed on this frequency difference, can now be utilised as done in ordinary Doppler radar, to measure the velocity of the aircraft, after making due allowance for the slant range.

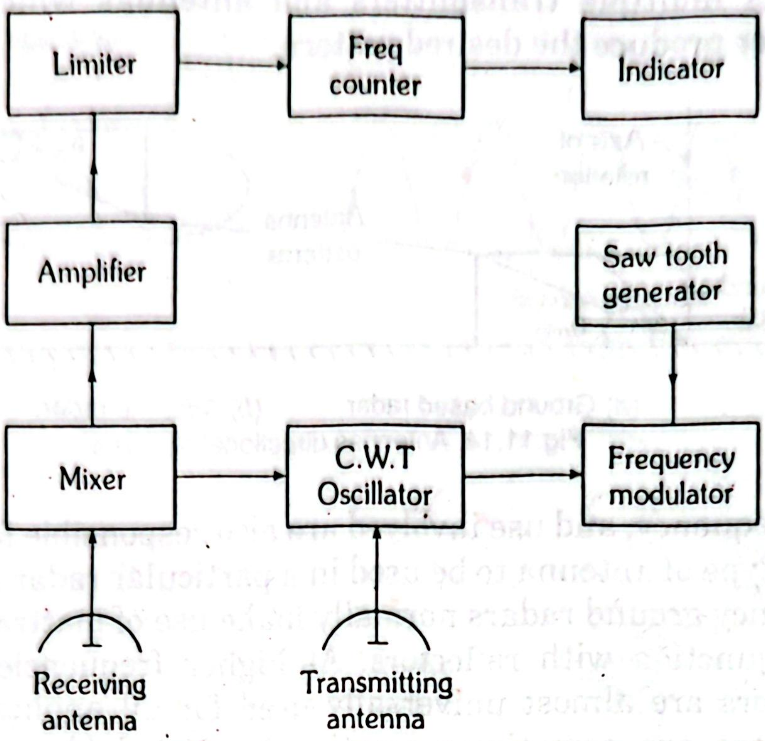
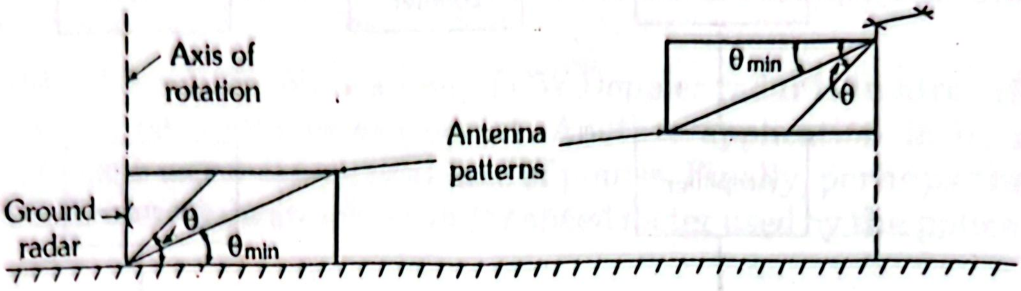


Fig. 11.13. Simple FM CW radar altimeter.

FM CW radar finds major application as an altimeter. It is preferred over pulsed radar because of the short ranges (heights) involved ; CW radar has no limit on the minimum range, whereas such limit exists in case of pulsed radar. Further, very simple, low power equipment can be used as in case of CW Doppler radar and use of small antennas is made possible because of size and proximity of earth ; thus reducing the size of the equipment even further.

Radar antenna Patterns. The shape of directive pattern required in a radar antenna, depends upon the application for which it is to be used. Thus, radars used to locate targets by searchlight techniques use pencil beams of a circular cross-section, whereas ground-based air-search radars normally make use of a beam with maximum possible azimuth resolution, but with a vertical pattern as shown in Fig. 11.14.

In this case some energy is radiated at high vertical angles to detect the presence of planes at these angles, but since the planes at such vertical angles will be closer to the radar, the transmitted energy at these positions is reduced than that at lower angles. *Height finder* radars, *i.e.* radars which are to give accurate measure of elevation of angles have a directivity in the vertical plane, which is much more than in horizontal plane. Antenna directivity and range is fairly important so that some complex radar systems, make use of multiple transmitters and antennas which combined together produce the desired pattern.



(*a*) Ground based radar (*b*) Airborne radar.
Fig.11.14. Antennas directional patterns.

Frequency, and use involved are also responsible for the choice of the type of antenna to be used in a particular radar system. Low frequency ground radars normally make use of mattress antennas in conjunction with reflectors. At higher frequencies, parabolic reflectors are almost universally used for all applications. Such reflectors are sometimes rotational paraboloids or cylindrical paraboloids ; they also often have portions cut away or are deformed to modify the shape of the pattern (for details refer to chapter on Antennas).

The directive gain of a radar antenna depends on the physical size of antenna measured in terms of wavelengths in accordance with the equation,

$$\text{Directive gain} = \frac{4\pi A_0 K}{\lambda^2}$$

where A_0 is actual area of antenna aperture

λ is wavelength, K a constant.

Radar antennas and scanning. Mostly all radar antennas use dipole or horn-fed paraboloid reflectors, or reflectors of basically paraboloid shape (namely the cut-paraboloid, parabolic cylinder, or pill box). In most of these, the beam width in the vertical direction (and therefore the angular resolution) is much worse than in the horizontal direction, but this is immaterial in ground to ground or even air to ground radars, and thus has an advantage of allowing a significantly reduced antenna size.

Antenna scanning. The radar antennas are made to scan a given area of the surrounding space, but the actual scanning pattern depends upon its application. Fig. 11.15 shows some typical scanning patterns.

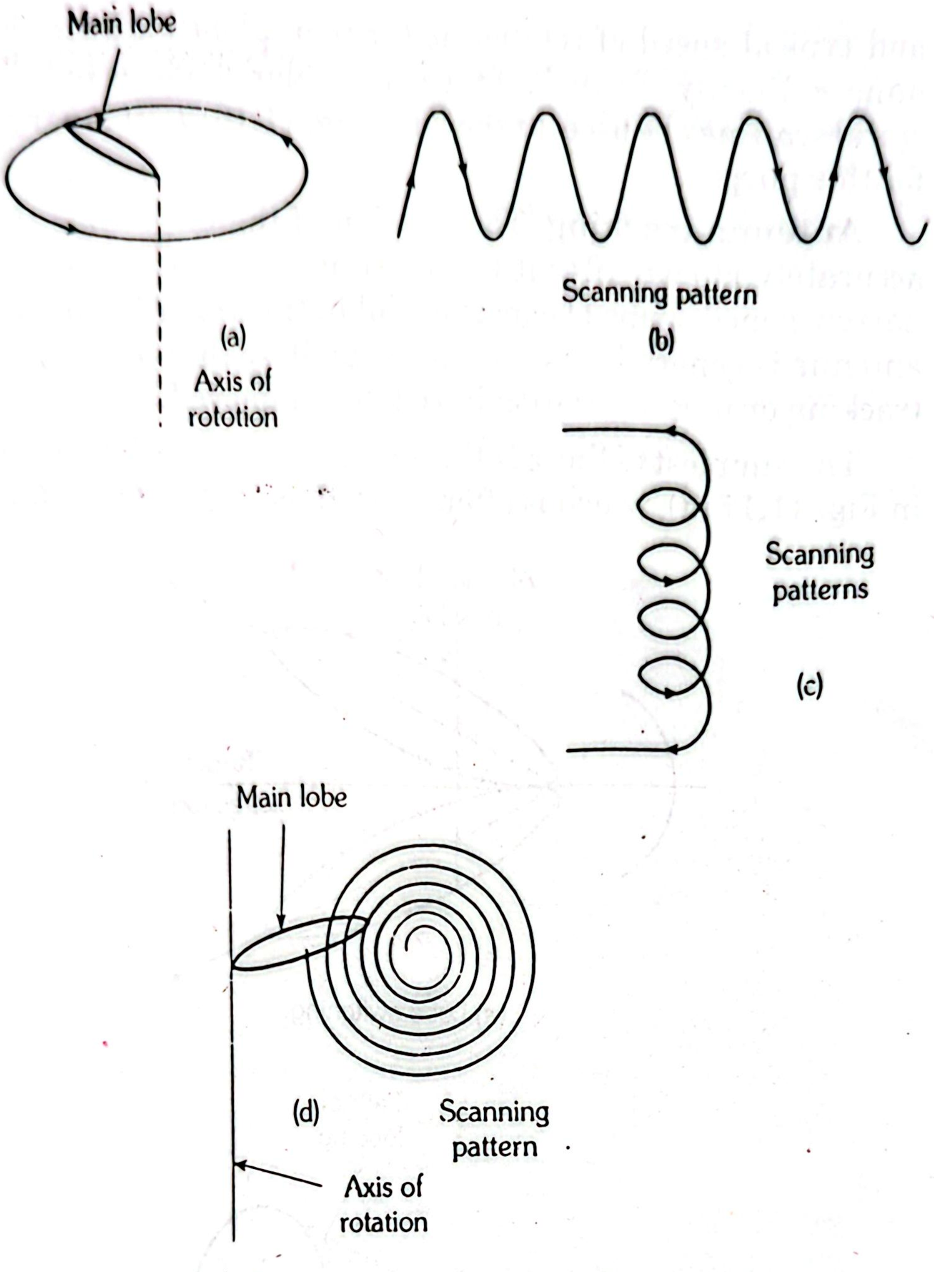
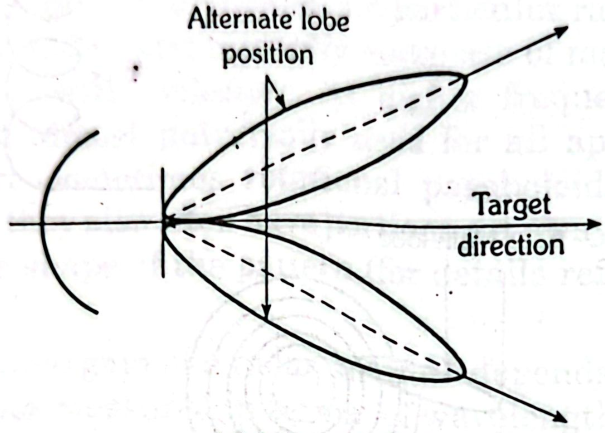

Main lobe
(a)
Axis of
rototion
Scanning pattern
(b)
Scanning
patterns
(c)
Main lobe
(d)
Scanning
pattern
Axis of
rotation

Fig.11.15. Representative antenna scanning patterns.
(*a*) Horizontal, (*b*) Nodding, (*c*) Helical, (*d*) Spiral.

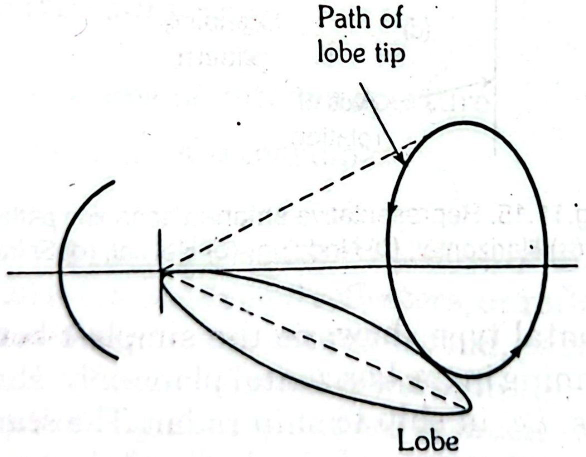
The horizontal type shown is the simplest but has the disadvantage of scanning in the horizontal plane only. However it is used at many places, *i.e.* in ship to ship radar. The scan shown in Fig. 11.16 (*b*) is an extension of the horizontal type scanning ; the antenna is rocked rapidly in elevation while it rotates more slowly in azimuth and thus scanning in both planes is performed. The system can be used to scan a particular sector as shown, or else it can be extended to cover the complete hemisphere. The helical scanning shown, can be used to search over the complete hemisphere ; here the elevation of the antenna is raised slowly, while it scans more rapidly in azimuth. The antenna is finally returned to its initial point after the completion of the scanning cycle, as shown, and typical speed of rotation is 6 r.p.m. alongwith a rise of 20% minute. Finally, if a limited area of circular shape is to be covered, spiral scan may be used, as shown in Fig. 11.16 (*d*); it is very popular for this purpose.

Antenna tracking. The location of the target has to be very accurately known after it has been acquired. An antenna with a narrow pencil shaped beam is useful in this regard, but this type of antenna is generally insufficient in itself, so that useful methods of tracking or precise location have to be employed.

The simplest of these is the *lobe-switching* technique as shown in Fig. 11.17 (*a*), which is often termed as *sequential lobing.*



(*a*) Lobe switching.



(*b*) Comical scanning.
Fig. 11.17. Antenna tracking.

The direction of the antenna beam is rapidly switched between two positions in this system, as shown, so that the strength of the echo from the target fluctuates at the switching frequency, unless the target is exactly midway between the two directions. In the latter case, the echo strength is same for both antenna positions, d the target is then tracked with much greater accuracy than ld have been achieved by simply pointing the antenna at it.

Conical scanning is an extension of sequential lobing, and is wn in Fig. 11.17 (*b*). The is obtained by mounting the parabolic enna slightly off centre and then rotating it about the axis of the abola as shown ; the rotation is slow compared to P.R.F. used.

The name conical scanning is derived from the surface described pace, by the pencil beam pattern of the antenna, as the tip of the tern moves in a circle. The same reasoning applies to target itioning as for sequential lobing, except that the conical scanning tem is accurate both in the elevation and in azimuth, whereas uential lobing is accurate in one plane only.

The two disadvantages associated with the use of either sequen- lobing or conical lobing are discussed. The first and the most ious disadvantage is that the motion of the antenna becomes e complex and therefore requires additional servo-mechanisms. second disadvantage is because of the fact that more than one rned pulses are required to locate a target. Infact, a minimum ur are required with conical scan, one for each extreme displace- t of the antenna. The effect of conical scanning or sequential ng for that matter, will be largely nullified if the target cross- ion is changing because of its change in altitude or because of ious other reasons ; so also will the echo power change. Hence ideal system would be the one in which all the information ained by conical scanning could be achieved with just one pulse. s system does exist and is known as a *monopulse*.

In an amplitude comparison monopulse system four feeds are d along with one paraboloid reflector. This system has four horn ennas placed about the central focus of the paraboloid reflector shown in Fig. 11.18.

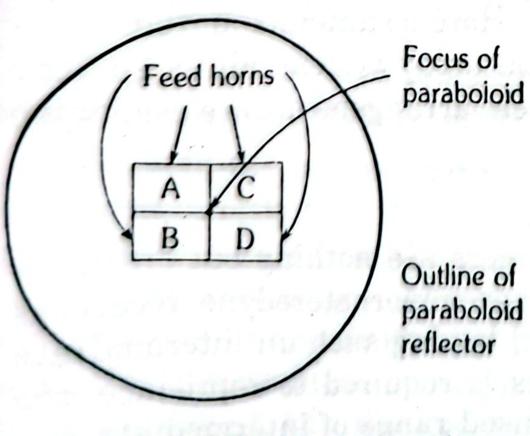


Fig. 11.18 Feed arangement for Monopulse tracking.

The transmitter feeds all the horns simultaneously. The sum signal transmitted is somewhat different from the usual pulse transmitted by a single horn. In receiver a duplexer using a hybrid ring or a rat-race is used to obtain the following three signals : the sum

This is because the echoes returned from one direction only are presented ; the antenna direction is indicated elsewhere.

Plan position indicator (PPI). The PPI shows a map of the target area, the CRT in this case being *Intensity Modulated*. Therefore the signal from the receiver, after demodulation is applied to the grid of the cathode Ray Tube, the CRT is biased slightly beyond cut off, and thus blips due to the targets, permit beam current, and therefore, result in screen brightness. The sawtooth scanning waveform is now applied to a pair of coils on opposite sides of the neck of the tube. Thus magnetic deflection is used and a sawtooth current is required for this. The coils are situated in a yoke similar to that of a TV picture tube and are rotated mechanically at the same angular velocity as the antenna, and hence the beam is not only deflected radially out from the centre and then back again rapidly, but it also rotates continuously around the tube. Therefore the brightness at any point on the screen indicates the presence of a target, the position corresponding to its actual physical position and the range being measured radially from the centre.

Normally long persistence phosphors are used so that the face f the PPI screen does not flicker since the scanning speed is lower than the 60 frames/sec. used in T.V. The resolution on the screen depends on beam width of the antenna, transmitted frequency, Pulse length and also on the diameter of the CRT beams. The PPI display systems are used with search radars particularly when conical scanning is employed. In an Aircraft, if the antenna does not point straight down, the range seen on the screen of PPI is not the true range ; it is the **Slant Range.**

Problem 11.1. (*a*) *Find the maximum range of a radar, the transmitted power is 250 kW, cross-sectional area of the target is 12.5 sq.m. minimum power received is* 10^{-3} *watt,* $G_R = 2000$ *and wavelength* $\lambda = 16$ *cm.*

(*b*) *Find maximum range when frequency is doubled.*

Solution.

(*a*) $$d_{max} = \sqrt[4]{\frac{P_T G_R^2 \lambda^2 S}{(4\pi)^3 P_{R_{min}}}}$$

Given $P_T = 250$ kW

$S = 12.5$ sq m

$G_R = 2000$

$$P_R = 10^{-3} \text{ watt}$$

$$d_{max} = \sqrt[4]{\frac{250 \times 10^3 \times (2000)^2 \times 12.5 \times (0.16)^2}{(4\pi)^3 \times 10^{-13}}}$$

$$= 200 \text{ km } \textbf{Ans.}$$

(*b*) We know

$$d_{max} \propto \sqrt{(\text{Frequency})}$$

$$\therefore \quad \propto \sqrt{\frac{1}{\lambda}}$$

$$\left(\frac{d_{max_1}}{d_{max_2}}\right) = \left(\frac{\lambda_2}{\lambda_1}\right)^{1/2}$$

$$= \left(\frac{f_1}{f_2}\right)^{1/2} = \left(\frac{1}{2}\right)^{1/2}$$

$$\therefore \quad d_{max_2} = \sqrt{2} \times 200$$

$$= 282 \text{ km } \textbf{Ans.}$$

Problem 11.2. *A radar has a beam angle of 1° and PPF of 240. A minimum of 8 reflections are required from a point target. Calculate the r.p.m. of the antenna drive motor.*

Solution. No. of power pulses per sec

$$= 240$$

∴ Time taken for 8 pulses

$$= \frac{8}{240} \text{ sec.}$$

In $\frac{8}{240}$ sec the antenna rotates by = 1°

So time taken for rotation of 360° *i.e.* one complete rotation

$$= \frac{8}{240} \times 360 = 12 \text{ sec.}$$

∴ No of revolutions of the antenna drive motor per minute

$$= \frac{60}{12} = 5 \textbf{ Ans.}$$